Appendix E - Angle offset and torque calculations

1 Introduction

This appendix covers calculations regarding the XTHT off-center lifting tool. A misalignment of the tool is the basis of the calculations, were the following items, which all represent chapters of the appendix, are calculated:

- Tilt of the XT
- Torque generated
- Risk of the tool to rotate on the spool
- Force acting on anti-rotation pin

The misalignment is shown in Figure 1. Such an angle misalignment relative to center of gravity (COG) will result in a tilt of the XT and generate torque to the tools locking mechanism. Page no. 2, 3, 4 and 5 covers symbols, formulas and reference figures, all relating to each other. Referring to the main report for design and explanations of the tool.

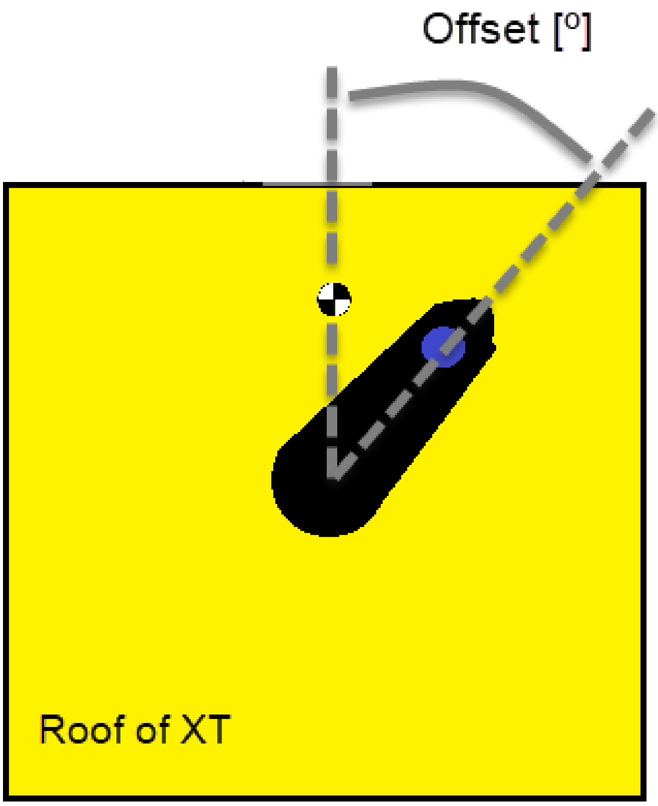

Figure 1: Angle misalignment towards COG. Top view.

A calculations sheet is made to find the highest values as the angle offset increases. This sheet is present in chapter 6.

Nomenclature

α	Angle misalignment of tool, XY-plane
β	Final tilt angle of the XT
μ	Coefficient of friction
ϕ	XT tilt angle, XZ-plane
θ	XT tilt angle, YZ-plane
D	Off center distance
F	Lifting load
F_N	Normal force to the tool, perpendicular on XY-plane
F_R	Resulting force that contributes to rotation
F_X	Force applied to the tool in YZ-plane
F_Y	Force applied to the tool in XZ-plane
F_F	Force of friction in tool locking mechanism
F_P	Force acting on anti-rotation pin
F_{X1}	Decomposed F_X, contribute to rotation
F_{Y1}	Decomposed F_Y, contribute to rotation
g	Gravitational acceleration coefficient
h	Distance down to COG
l	Distance from spool center to locking dogs engagement area
O	Total offset distance from lifting point to COG, XY-plane
S	Safety against rotation
T	Torque generated
W	Weight of XT
x	Distance from lifting point to COG, XZ-plane
y	Distance from lifting point to COG, YZ-plane

Formulas

XT tilt angle, XZ-plane [°]

$$\phi = \arctan\left(\frac{x}{h}\right) = \arctan\left(\frac{D - \cos\alpha * D}{h}\right)$$

XT tilt angle, YZ-plane [°]

$$\theta = \arctan\left(\frac{y}{h}\right) = \arctan\left(\frac{\sin\alpha * D}{h}\right)$$

Total offset distance, XY-plane [mm]

$$O = \sqrt{x^2 + y^2} = \sqrt{(D - \cos\alpha * D)^2 + (\sin\alpha * D)^2}$$

Final tilt angle of the XT [°]

$$\beta = \arctan\left(\frac{O}{h}\right)$$

Normal Force [N]

$$F_N = \cos\beta * F = \cos\beta * W * g$$

Rotational force [N]

$$F_R = F_{y1} + F_{x1} = F_Y * \cos\alpha + F_X * \sin\alpha = F * \sin\theta * \cos\alpha + F * \sin\phi * \sin\alpha$$

$$F_R = W * g(\sin\theta * \cos\alpha + \sin\phi * \sin\alpha)$$

Torque [Nm]

$$T = D * F_R$$

Safety against rotation [-]

$$S = \frac{F_F * l}{T} = \frac{F_N * \mu * l}{T}$$

Reference figures

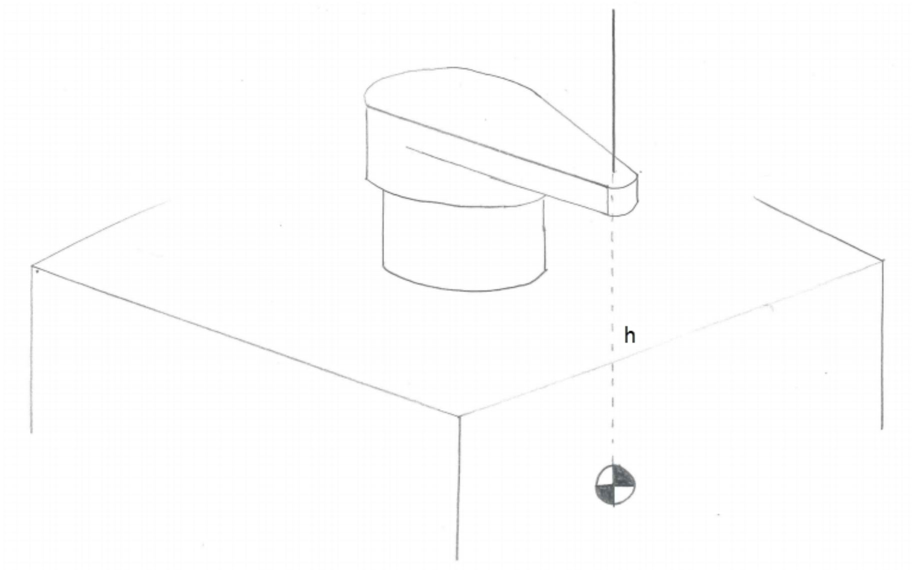

Figure 2: Correct lifting above COG

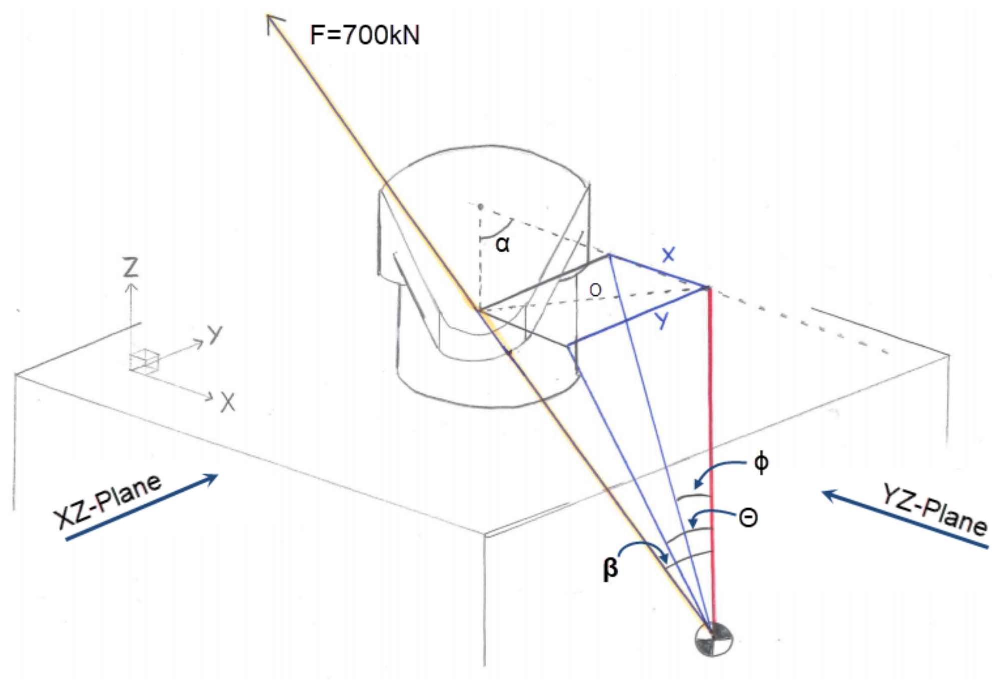

Figure 3: Incorrect lifting

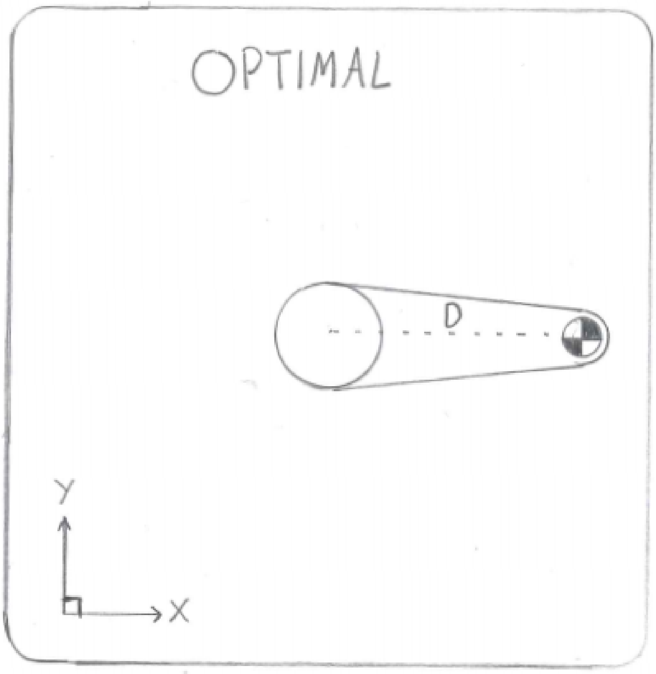

Figure 4: Top view - Correct

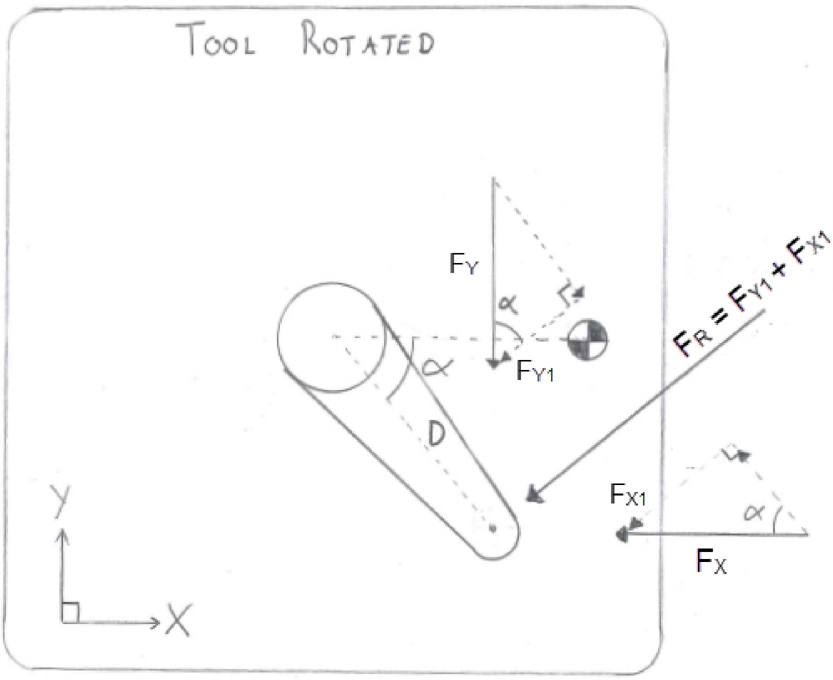

Figure 5: Top view - Incorrect

2 Calculation basis and values

Table 1 shows the variables of the calculations. The calculations use the shown values as basis. The values are all conservative and represent a worst case scenario. For example, the tilt and torque will be higher with an increased off-center distance, and there by the maximum distance at 0.5m is set. In the calculation sheet, the values can be changed if desirable.

All the values is sourced from different appendix, shown in the following list.

Calculation variables

Explanation	**Symbol**	**Value**	**Unit**
Distance down to COG	h	2	meter
Off center distance	D	0.5	meter
Distance from center to locking dogs	l	0.3	meter
XT weight	W	70	tonnes
Friction coefficient, steel on steel	μ	0.02	
Anti-rotation pin radius	N/A	0.5	meter

Table 1: Values

Sources:

- Distance down to COG - Main report
- Maximum off-center distance - Appendix A - Design Basis
- Distance from center to locking dogs - Material Nr. 10014224 - XT Handling tool
- XT weight - Appendix A - Design Basis
- Anti-rotation pin radius - Main report
- Friction coefficient - Based conversations with Aker Solutions, 0.02 were chosen to have a conservative value.

3 Tilt of the XT

This chapter covers calculations of how the XT tilt due to a angle misalignment, as shown in Figure 1.

As α increases, the tool starts to tilt. The final tilt angle of the XT is based on the distance down to COG and the combined offset in the XY-plane. The tilt angle is thereby expressed as follows:

$$\beta = \arctan\left(\frac{O}{h}\right)$$

Where "O" is expressed by:

$$O = \sqrt{x^2 + y^2} = \sqrt{(D - \cos\alpha * D)^2 + (\sin\alpha * D)^2}$$

Inserting the values from Table 1 give the final tilt of the XT $[\beta]$ as a function of α:

$$\beta(\alpha) = \arctan\left(\frac{\sqrt{(0.5m - \cos\alpha * 0.5m)^2 + (\sin\alpha * 0.5m)^2}}{2m}\right) \quad [^\circ]$$

The graph in Figure 6 shows the how much the XT tilts as the angle offset increases. The maximum XT tilt angle is at 26.6°at 180°misalignment, referring to chapter 6.

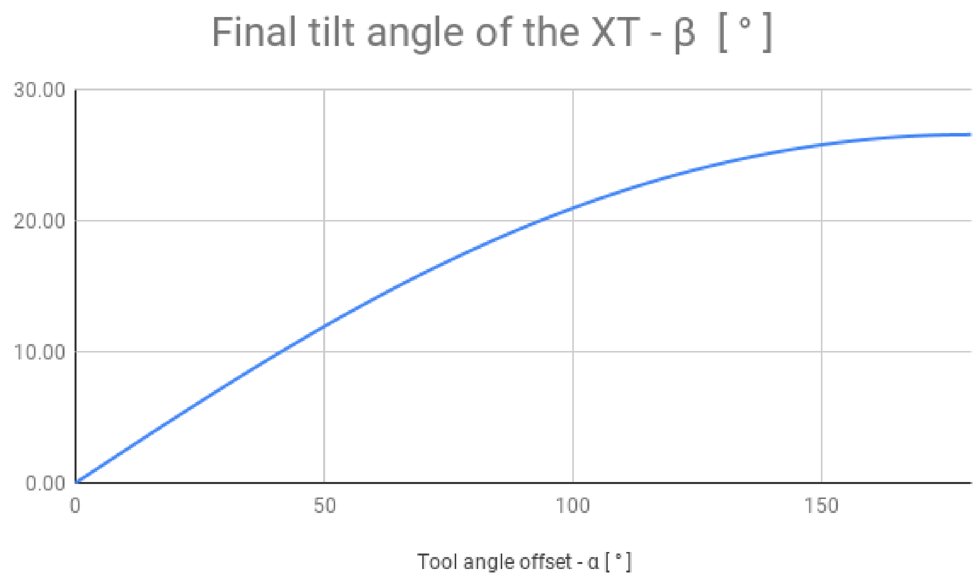

Figure 6: Final XT tilt

Figure 7 shows the how the XT tilts in the different planes. θ corresponds to the YZ plane, while ϕ corresponds to the XZ-plane.

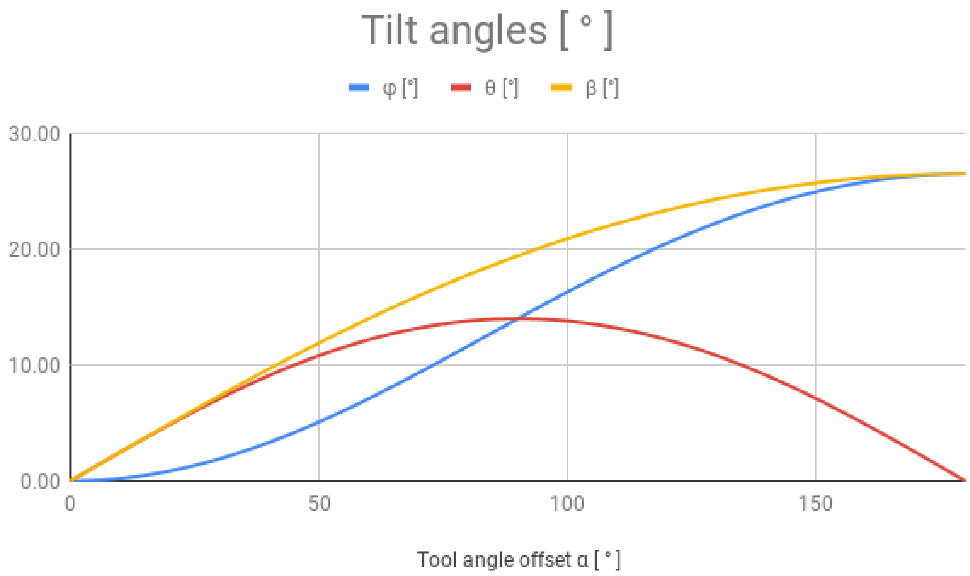

Figure 7: All tilt angles

4 Torque generated

This chapter covers calculations of how much torque that is generated as the angle offset $[\alpha]$ increases. The torque applied to the tool is expressed as follows:

$$T = D * F_R$$

Where D is the off-center distance of the lifting point, and F_R the resulting force that contributes to rotation around the Z-axis. The chosen approach to find F_R, is by considering both the XZ-plane and the YZ-plane. First of all, the tilt in the different planes need to be settled.

$$\theta = \arctan\left(\frac{y}{h}\right) = \arctan\left(\frac{\sin\alpha * D}{h}\right)$$

$$\phi = \arctan\left(\frac{x}{h}\right) = \arctan\left(\frac{D - \cos\alpha * D}{h}\right)$$

Where θ corresponds to the YZ plane, while ϕ corresponds to the XZ-plane. To express the different tilts as a function of α, values from Table 1 is inserted:

$$\theta(\alpha) = \arctan\left(\frac{y}{h}\right) = \arctan\left(\frac{\sin\alpha * 0.5m}{2m}\right) \quad [^\circ]$$

$$\phi(\alpha) = \arctan\left(\frac{x}{h}\right) = \arctan\left(\frac{0.5m - \cos\alpha * 0.5m}{2m}\right) \quad [^\circ]$$

The forces that contributes to rotation at the tool are be expressed as follows:

$$F_Y = F * \sin\theta$$

$$F_X = F * \sin\phi$$

As Figure 5 shows, F_Y and F_R is not working perpendicular to the side of the tool. How much the two forces contributes to rotation varies as α increases. For example, at $\alpha = 90^\circ$ would F_X contribute to the rotation all alone, while F_Y would only contribute to tension along the tool's cantilever. The forces is therefore decomposed to find the forces which contributes to rotation. Figure 5 shows the forces.

$$F_{Y1} = F_Y * \cos\alpha$$

$$F_{X1} = F_X * \sin\alpha$$

Adding these two forces together gives the resulting force which contributes to rotation of the tool around the Z-axis.

$$F_R = F_{Y1} + F_{X1} = F_Y * \cos\alpha + F_X * \sin\alpha = F * \sin\theta * \cos\alpha + F * \sin\phi * \sin\alpha$$

$$\Downarrow$$

$$F_R = F * (\sin\theta * \cos\alpha + \sin\phi * \sin\alpha)$$

The next page shows the formula extended and as a function of α.

$$F_R = F * (\sin\theta * \cos\alpha + \sin\phi * \sin\alpha)$$

$$\Downarrow$$

$$F_R(\alpha) = F * \left[\sin\left(\arctan\left(\frac{\sin\alpha * D}{h} \right) \right) * \cos\alpha + \sin\left((\arctan\left(\frac{D - \cos\alpha * D}{h} \right) \right) * \sin\alpha \right] \quad [^\circ]$$

$$\Downarrow$$

$$F_R(\alpha) = 700'000N * \left[\sin\left(\arctan\left(\frac{\sin\alpha * 0.5m}{2m} \right) \right) * \cos\alpha + \right.$$

$$\left. \sin\left((\arctan\left(\frac{0.5m - \cos\alpha * 0.5m}{2m} \right) \right) * \sin\alpha \right] \quad [^\circ]$$

Finally, the torque as a function of α is expressed as:

$$T(\alpha) = 0.5m * F_R(\alpha) \quad [Nm]$$

The graph in Figure 8 shows the torque generation as the angle offset increases. The maximum torque is at 85013Nm at $\alpha = 87^\circ$, referring to 6.

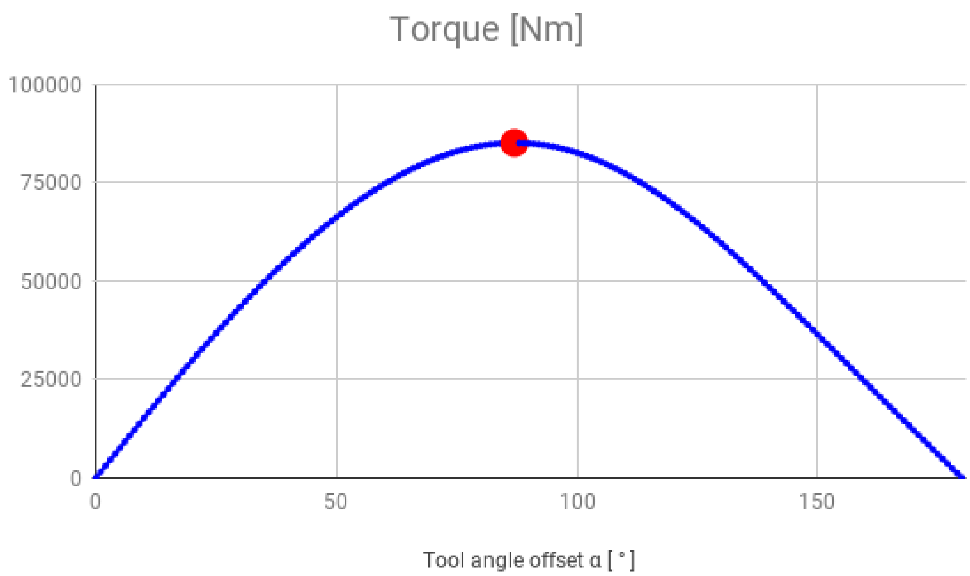

Figure 8: Torque generated to tool due to misalignment

Note: This note applies for the whole chapter and mentioned that the F_Y force is working a long with ZY-plane and is perpendicular to the XZ-plane, and the F_X force works the other way round.

5 Risk of the tool to rotate on the spool

This chapter calculates the safety factor which represent the risk of the tool to rotate on the spool due to an angle offset at α.

The calculations is based on having no anti-rotation devices acting during the tilted lift. The only factor which prevents the tool from rotating is the counter torque generated by friction in the locking mechanism of the tool. Thus, the safety factor is expressed as:

$$S = \frac{F_F * l}{T}$$

Where F_F and l represent the force of friction in the tools locking mechanism and the length from spool center to the locking mechanism engagement area, respectively. The force of friction is generated from the normal force which acts to the tool, multiplied with the coefficient of friction, as shown underneath.

$$F_F = F_N * \mu$$

The normal force F_N is the one decomposed force from F which acts perpendicularly to the tool. The force varies by the tilt of the XT and is expressed as follows:

$$F_N = F * \cos\beta$$

The extended version of the safety factor could then be expressed as:

$$S = \frac{F_N * \mu * l}{T} = \frac{F * \cos\beta * \mu * l}{T}$$

And as a function of α as:

$$S(\alpha) = \frac{700000N * \cos\beta(\alpha) * 0.02 * 0.3m}{0.5m * F_R(\alpha)} \quad [-]$$

The calculation sheet in chapter 6 shows that the safety factor is below zero, resulting in a rotation. It is worth to mentioned that the coefficient of friction (μ) is very conservative and that a higher factor would drastically change the result. An typical friction coefficient at a dry steel on steel connection have a value at 0.78 (See the main report for source). According to the calculation sheet, would such a friction coefficient give a safety value of 15.8 against rotation.

However could a wet or greasy connection result in rotation hazards for the tool, and therefore must an additional anti-rotation device be present. The calculations regarding this device is covered in the next chapter.

Force acting on anti-rotation pin

This chapter coves how much force that would act on the anti-rotation pin due to an angle misalignment at α. The force acting on the pin is based on the generated torque and the distance from spool center to the pin. The anti-rotation pin radius is is determined at 0.5m, referring to main report. The force acting on the pin is expressed as:

$$F_P = \frac{T}{D}$$

Force acting on the pin as a function of α:

$$F_P(\alpha) = \frac{0.5m * F_R(\alpha)}{0.5m}$$

In this calculations, D is equal to the anti-rotation pin radius and thereby $F_P = F_R$.

Note: Friction has been neglected to provide a more conservative approach

6 Calculation sheet

The values of the calculation sheet is based on the values stated in Table 1 and calculations covered in this appendix. The green line represents when the tree tilts 1.7°, which is the acceptance criteria for maximum β, referring to appendix A - Design Basis. The yellow line represent the highest torque/T, while the blue line represent the highest XT tilt/β.

α [°]	φ [°]	θ [°]	O [mm]	β [°]	Normal force [N]	Rotational force [N]	Torque [Nm]	Safety	Force at anti-rotatin pin [N]
0	0.00	0.00	0	0.00	700000	0	0		0
6.81	0.10	1.70	59	1.70	699692	20742	10371	0.4	20742
10	0.22	2.49	87	2.50	699336	30360	15180	0.3	30360
20	0.86	4.89	174	4.96	697376	59649	29824	0.1	59649
30	1.92	7.13	259	7.37	694211	86908	43454	0.1	86908
40	3.35	9.13	342	9.70	689984	111351	55676	0.1	111351
50	5.10	10.84	423	11.93	684877	132330	66165	0.1	132330
60	7.13	12.22	500	14.04	679100	149253	74627	0.1	149253
70	9.34	13.22	574	16.00	672876	161521	80760	0.0	161521
80	11.67	13.83	643	17.82	666427	168529	84264	0.0	168529
87	13.33	14.02	688	18.99	661894	170027	85013	0.0	170027
90	14.04	14.04	707	19.47	659966	169775	84887	0.0	169775
100	16.35	13.83	766	20.96	653690	165027	82514	0.0	165027
110	18.55	13.22	819	22.27	647773	154475	77238	0.1	154475
120	20.56	12.22	866	23.41	642364	138796	69398	0.1	138796
130	22.33	10.84	906	24.38	637590	119084	59542	0.1	119084
140	23.82	9.13	940	25.17	633554	96655	48327	0.1	96655
150	25.01	7.13	966	25.78	630336	72776	36388	0.1	72776
160	25.87	4.89	985	26.22	627996	48424	24212	0.2	48424
170	26.39	2.49	996	26.48	626575	24131	12065	0.3	24131
180	26.57	0.00	1000	26.57	626099	0	0	0.0	0